

The Solar Cycle

and,
How Do We Know What We Know?

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The Sun and Solar Activity

The Sun: a Few Numbers

Mass = $1.99 \cdot 10^{30}$ kg (= $1 M_{\odot}$)

Average density = 1.4 g/cm^3

Luminosity = $3.84 \cdot 10^{26}$ W (= $1 L_{\odot}$)

Effective temperature = 5777 K (G2 V)

Core temperature = $15 \cdot 10^6$ K

Surface gravitational acceleration $g = 274 \text{ m/s}^2$

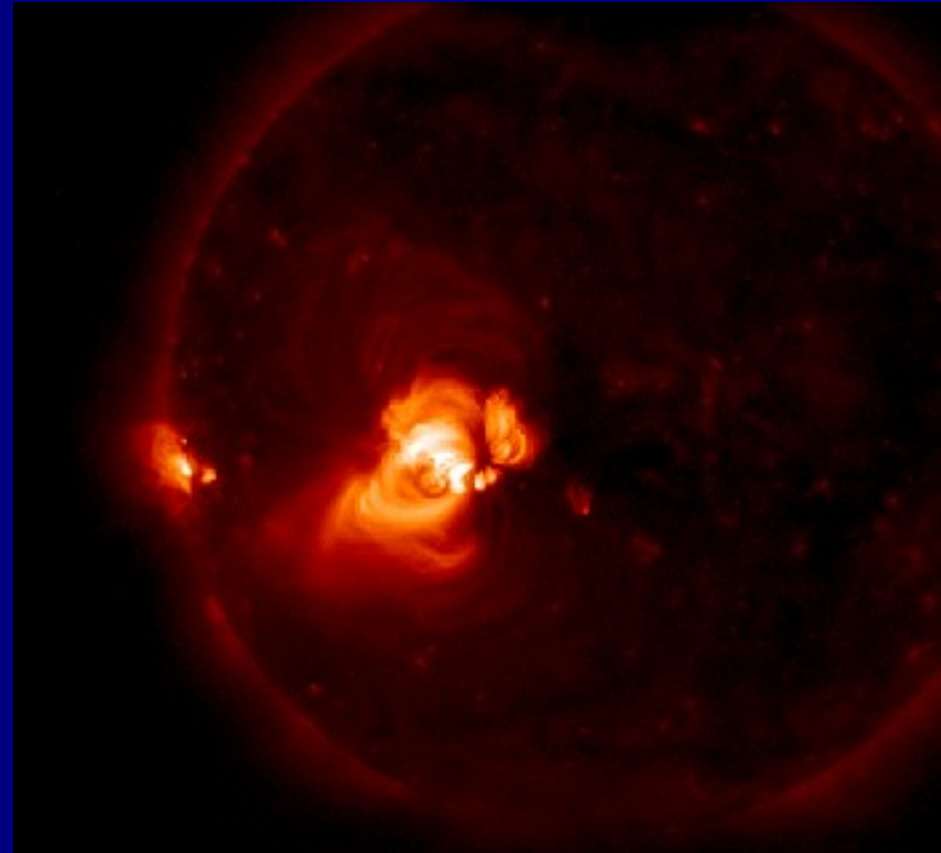
Age = $4.55 \cdot 10^9$ years (from meteorite isotopes)

Radius = $6.96 \cdot 10^5$ km

Distance = 1 AU = $1.496 (+/-0.025) \cdot 10^8$ km

1 arc sec = 722 ± 12 km on solar surface (elliptical Earth orbit)

Rotation period = 27 days at equator (sidereal, i.e. as seen from Earth; Carrington rotation)



The Convection Zone

Energy continues to move toward the surface through convection currents of heated and cooled gas in the convection zone.

The Corona

The ionized elements within the corona glow in the x-ray and extreme ultraviolet wavelengths. NASA instruments can image the Sun's corona at these higher energies since the photosphere is quite dim in these wavelengths.

The Radiative Zone

Energy moves slowly outward—taking more than 170,000 years to radiate through the layer of the Sun known as the radiative zone.

Sun's Core

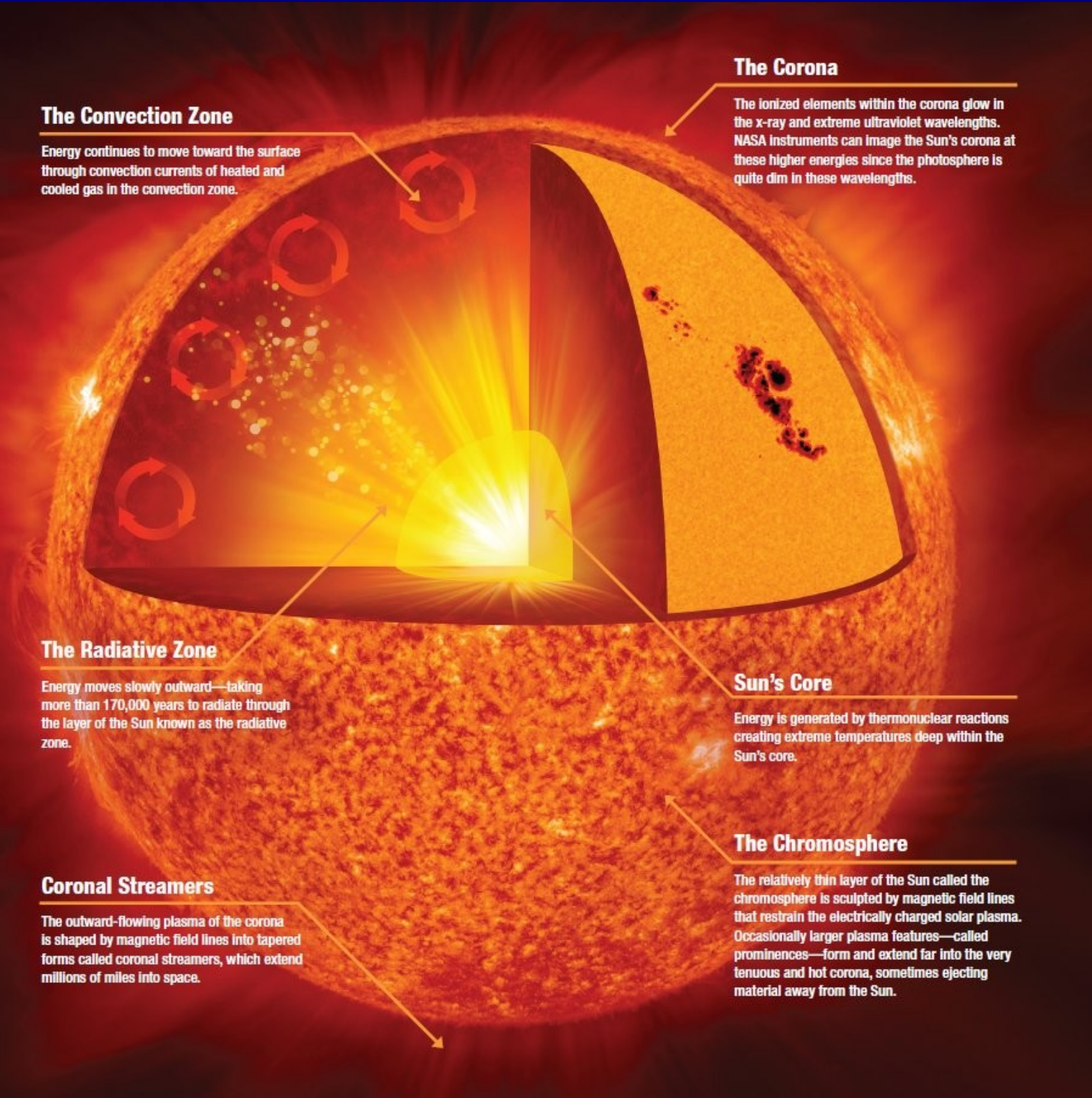
Energy is generated by thermonuclear reactions creating extreme temperatures deep within the Sun's core.

Coronal Streamers

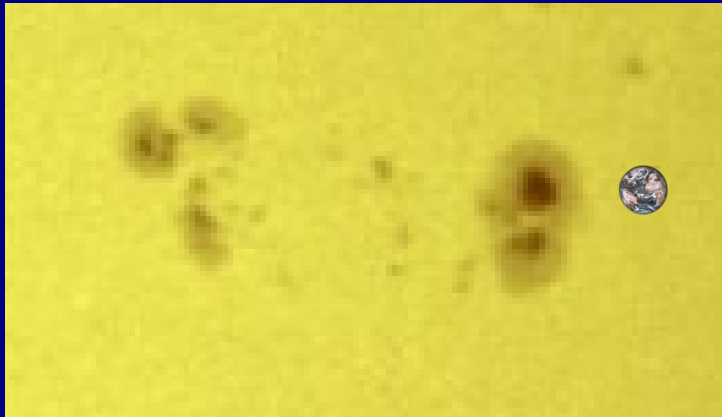
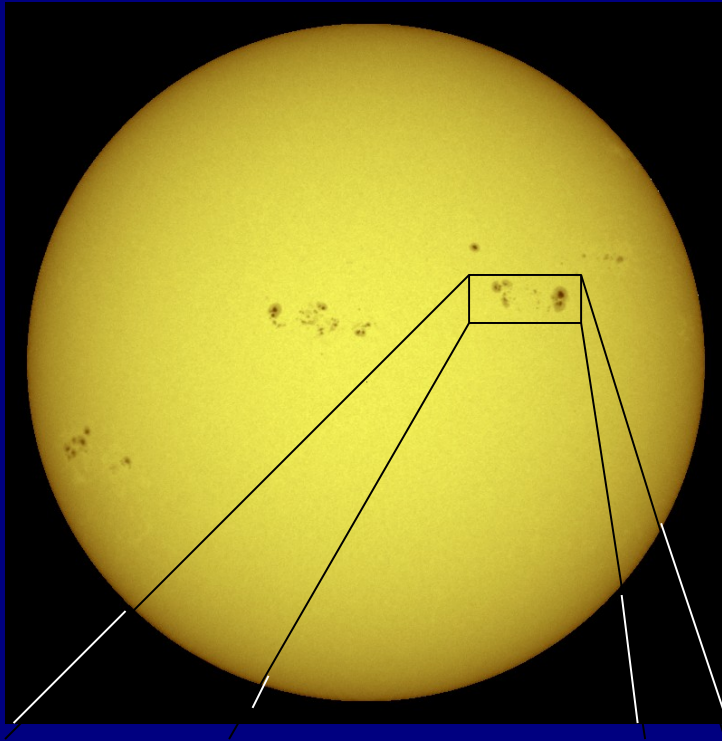
The outward-flowing plasma of the corona is shaped by magnetic field lines into tapered forms called coronal streamers, which extend millions of miles into space.

The Chromosphere

The relatively thin layer of the Sun called the chromosphere is sculpted by magnetic field lines that restrain the electrically charged solar plasma. Occasionally larger plasma features—called prominences—form and extend far into the very tenuous and hot corona, sometimes ejecting material away from the Sun.



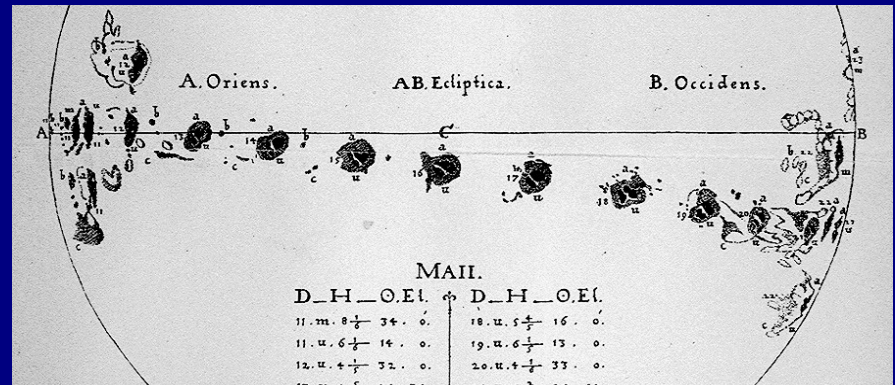
Sunspots



Sunspots are dark (and cooler) regions on the surface of the Sun. They have a darker inner region (the Umbra) surrounded by a lighter ring (the Penumbra).

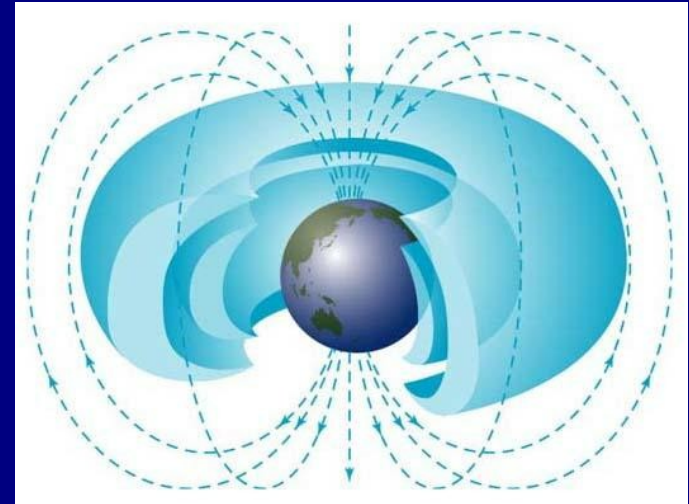
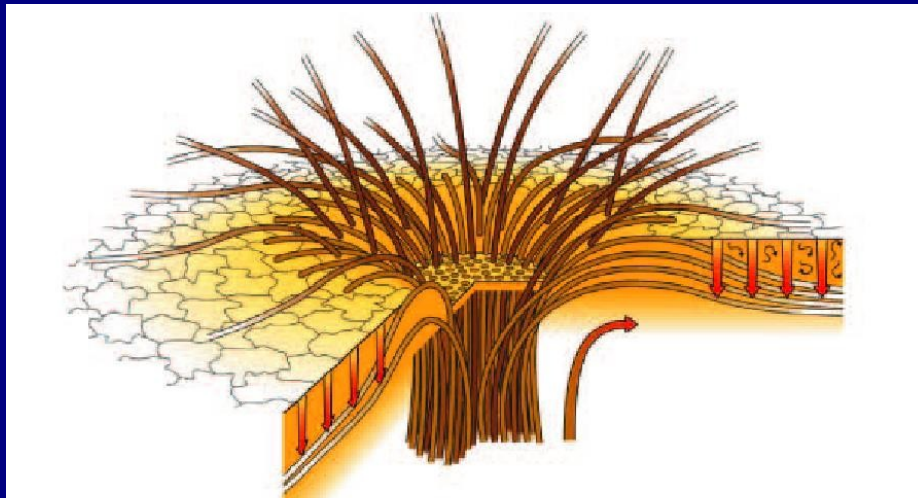
Sunspots usually appear in groups that form over hours or days and last for days or weeks.

The earliest sunspot observations (c. 1609) indicated that the Sun rotates once in about 27 days.



Sunspot Structure

Sunspots are regions where intense magnetic fields break through the surface of the Sun. The magnetic field strengths are typically about 6000 times stronger than the Earth's magnetic field.



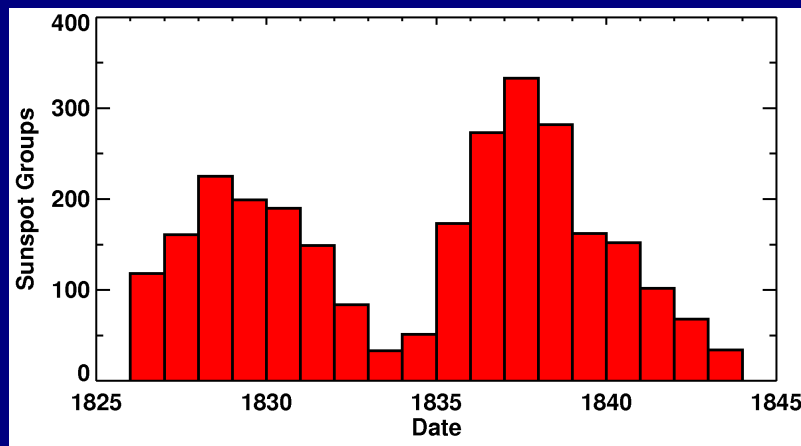
Magnetic fields and the ionized gases within the Sun are intimately tied together. Where magnetic pressure dominates – the gas follows the magnetic field. Where gas pressure dominates – the magnetic field follows the gas. In sunspots the magnetic pressure dominates – this inhibits the convective transport of heat and makes sunspots cooler.

The Solar Cycle

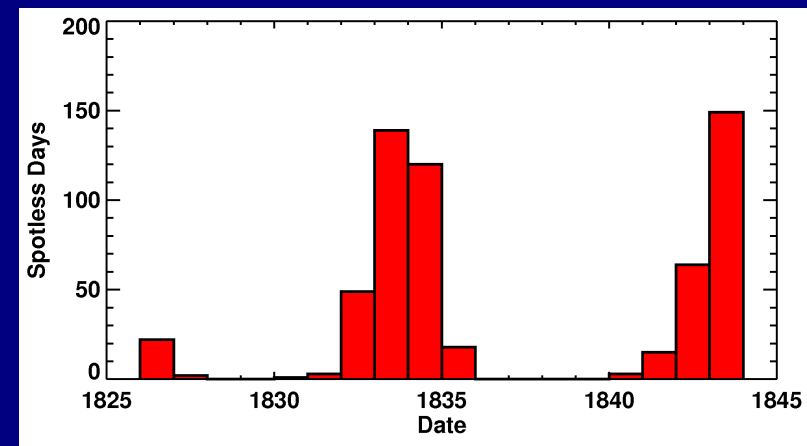
Sunspot Cycle Discovery

Astronomers had been observing sunspots for over 230 years before Heinrich Schwabe, an amateur astronomer in Dessau, Germany, discovered in 1844 that the number of sunspot groups and the number of days without sunspots increased and decreased in cycles of about 10-years.

Schwabe's data for 1826 to 1843

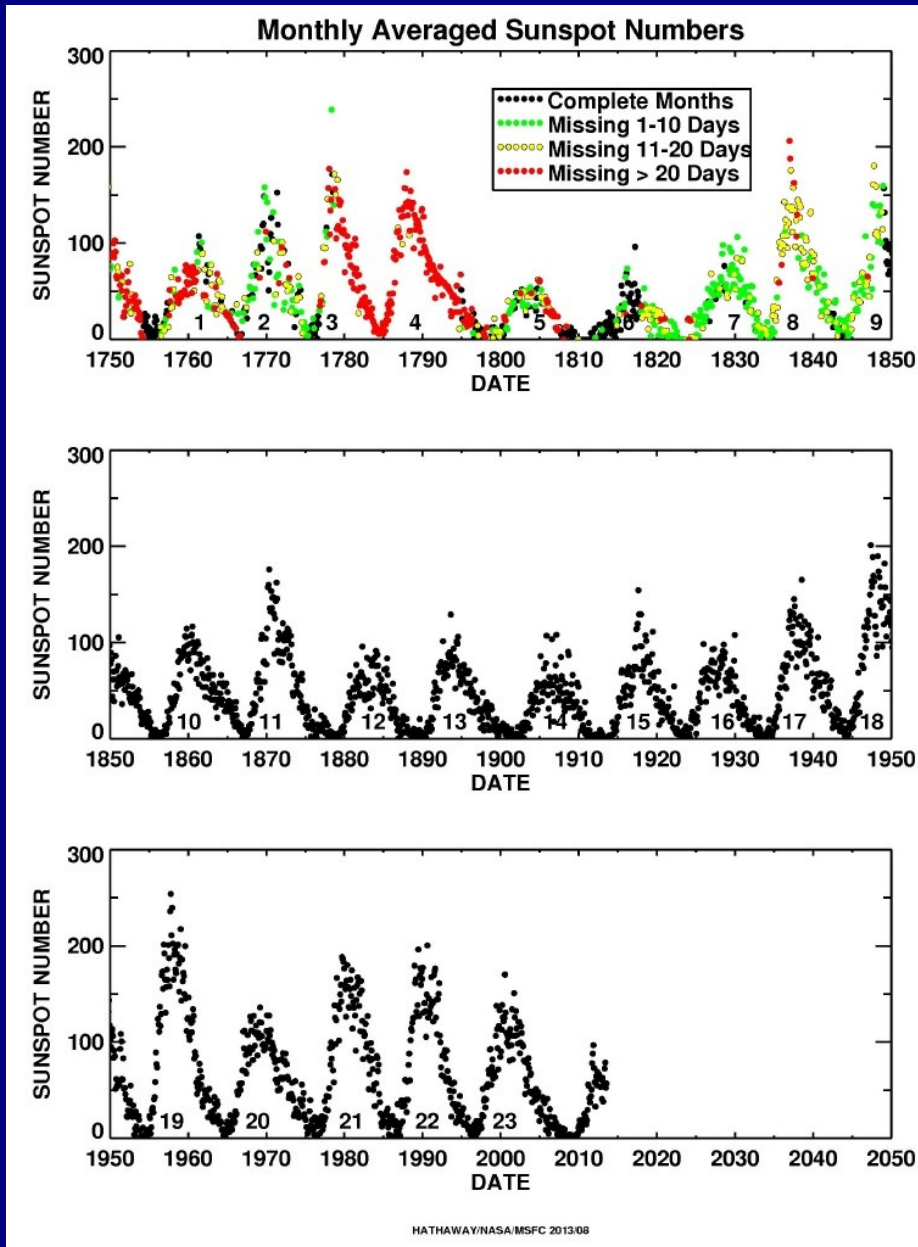


Number of Sunspot Groups per Year



Number of Spotless Days

23 Full Cycles



Shortly after Schawbe discovery Rudolf Wolf proposed using a “Relative” Sunspot Number count. While there were many days without observations prior to 1849, sunspots have been counted on every day since. To this day we continue to use Wolf’s Relative Sunspot Number and his cycle numbering.

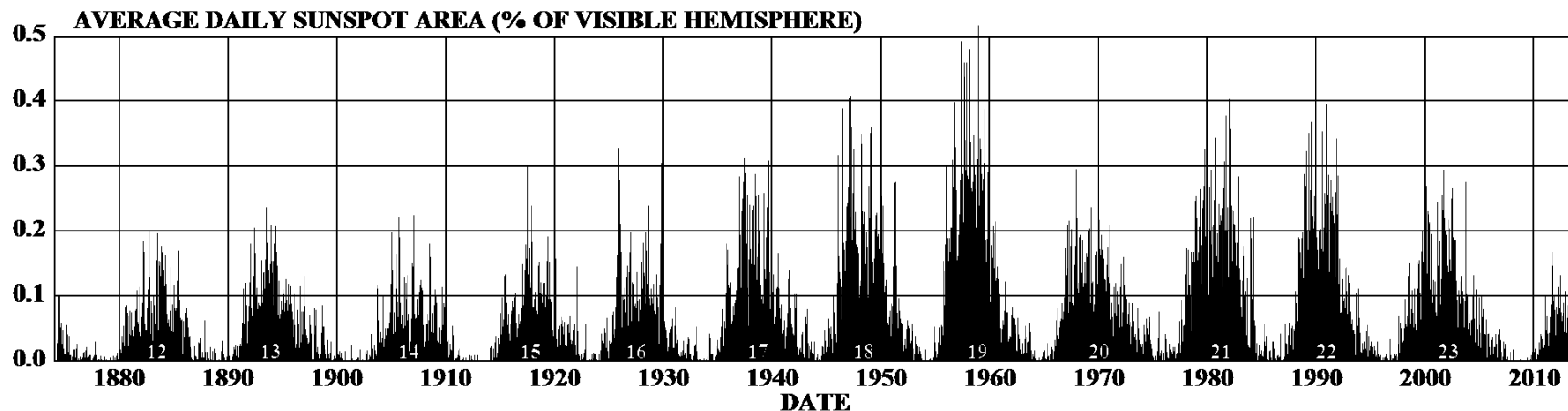
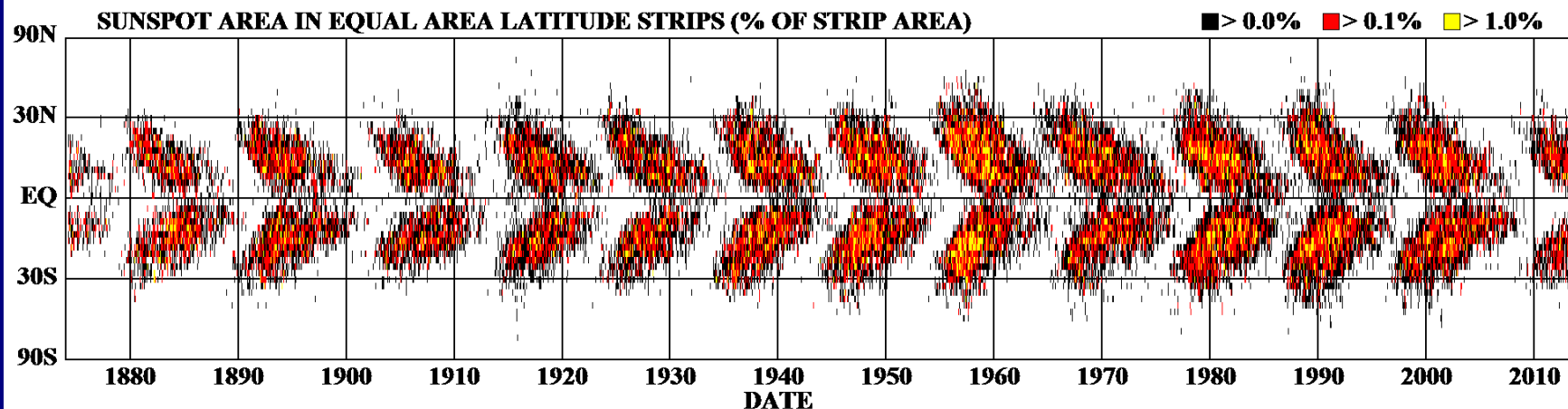
The average cycle lasts about 11 years, but with a range from 9 to 14.

The average amplitude is about 100, but with a range from 50 to 200.

Sunspot Latitudes

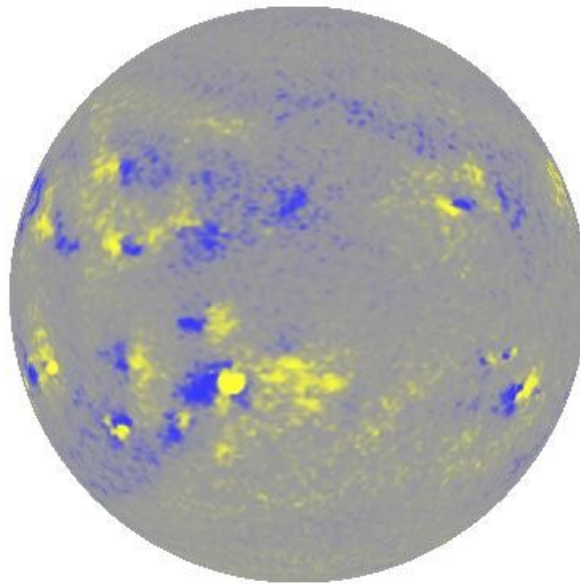
Sunspots appear in two bands on either side of the equator. These bands drift toward the equator as the cycle progresses. Big cycles have wider bands that extend to higher latitudes. Cycles overlap by 2-3 years.

DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS

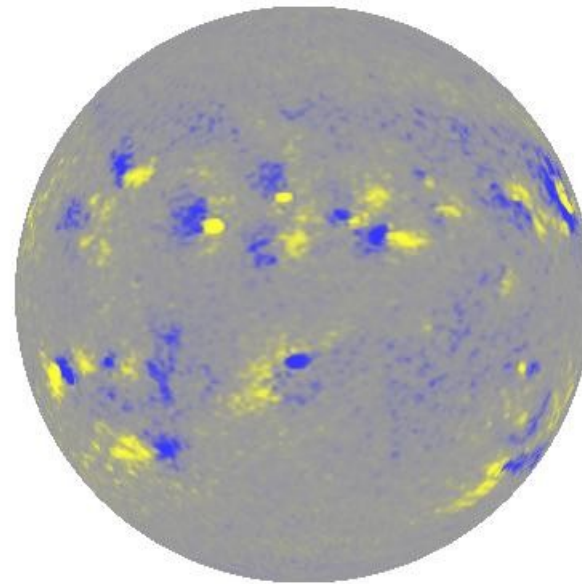


Hale's Magnetic Polarity Law

In 1919 Hale (along with Ellerman, Nicholson, and Joy) found that the magnetic field in sunspots followed a definite law, “Hale’s Law” such that: *“...the preceding and following spots ... are of opposite polarity, and that the corresponding spots of such groups in the Northern and Southern hemispheres are also opposite in sign. Furthermore, the spots of the present cycle are opposite in polarity to those of the last cycle”*.



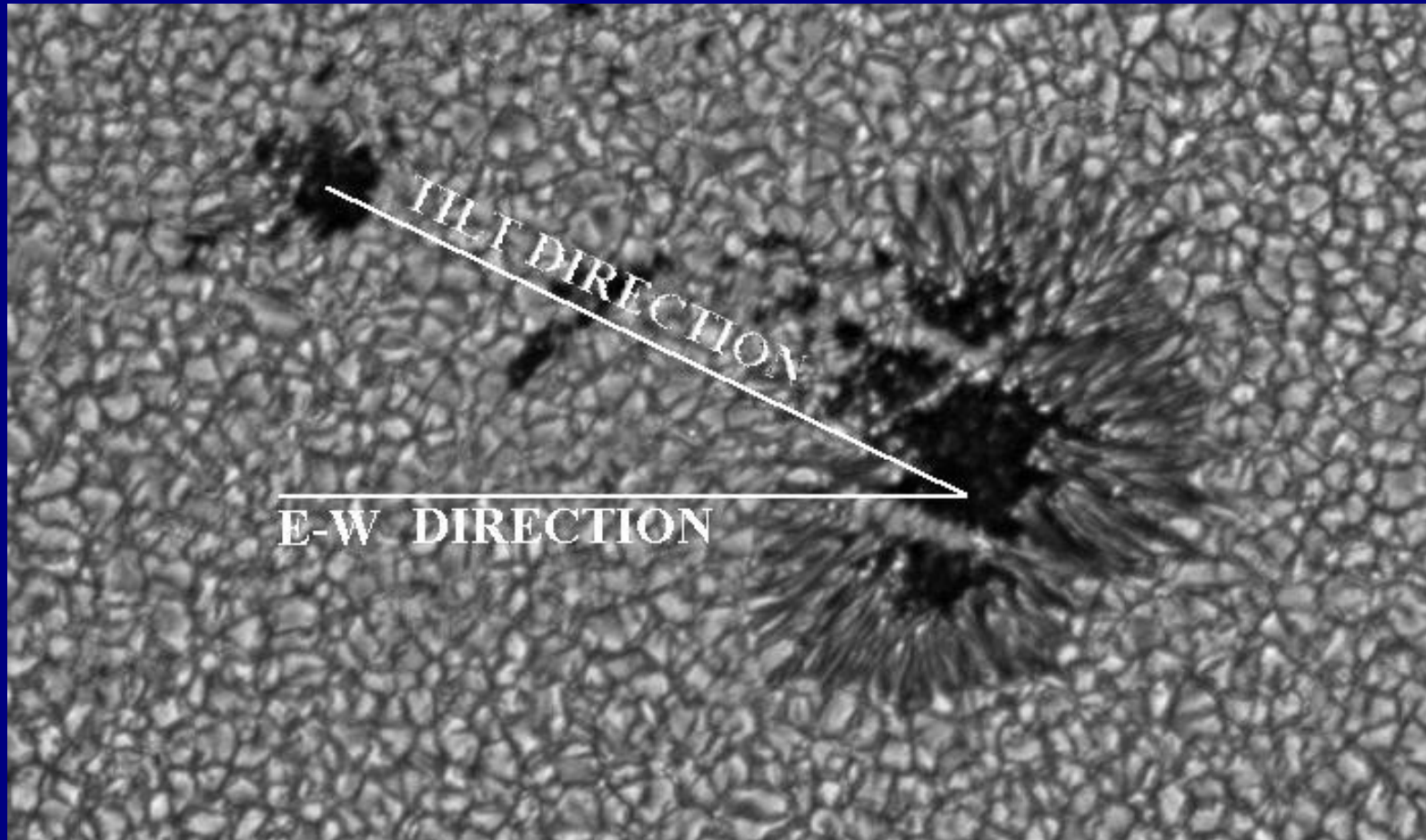
Cycle 22
1989 August 02



Cycle 23
2000 June 26

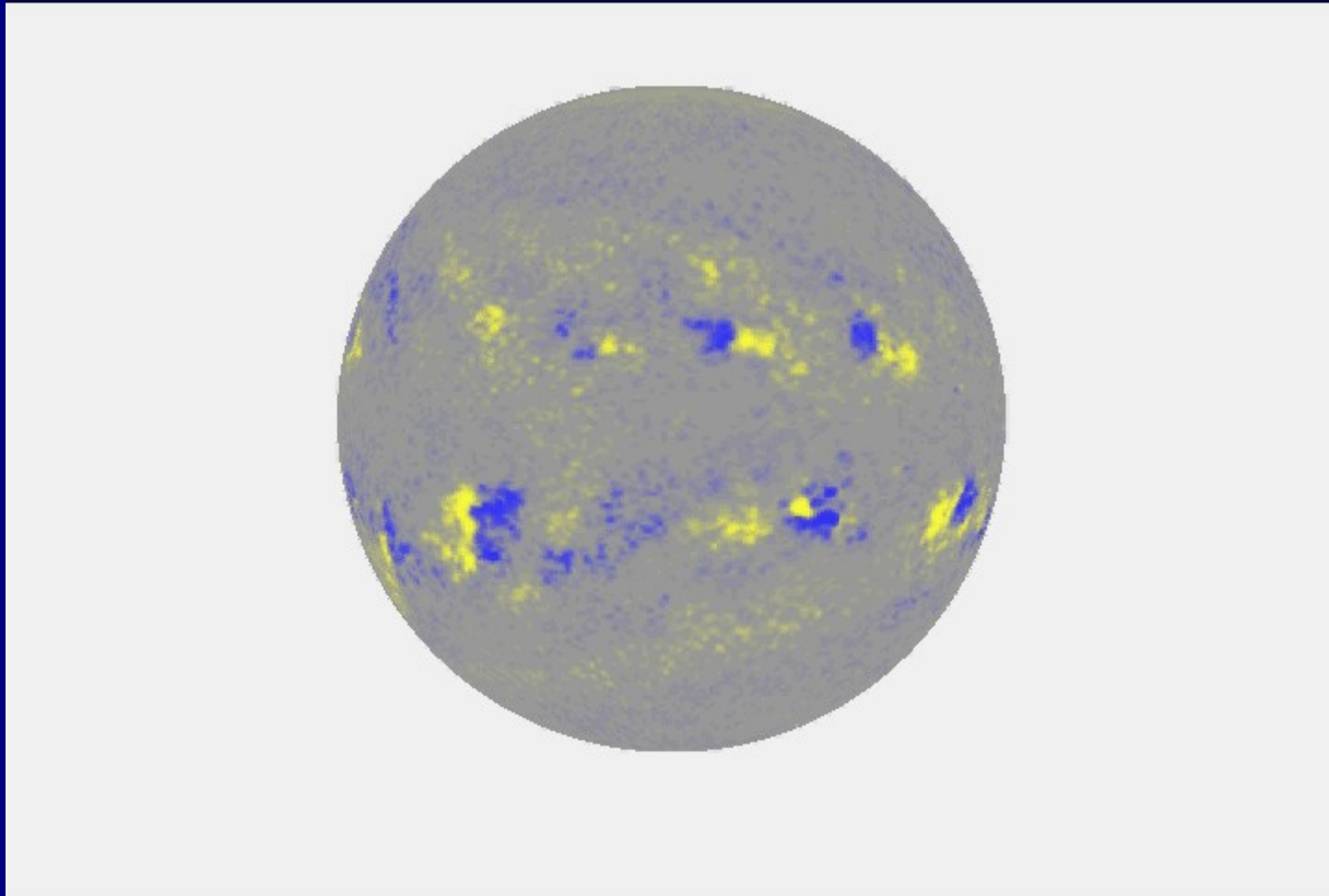
Active Region Tilt- Joy's Law

In that same 1919 paper Joy noted that sunspot groups are tilted with the leading spots closer to the equator than the following spots. This tilt increases with latitude.



Three Solar Cycles in 3D

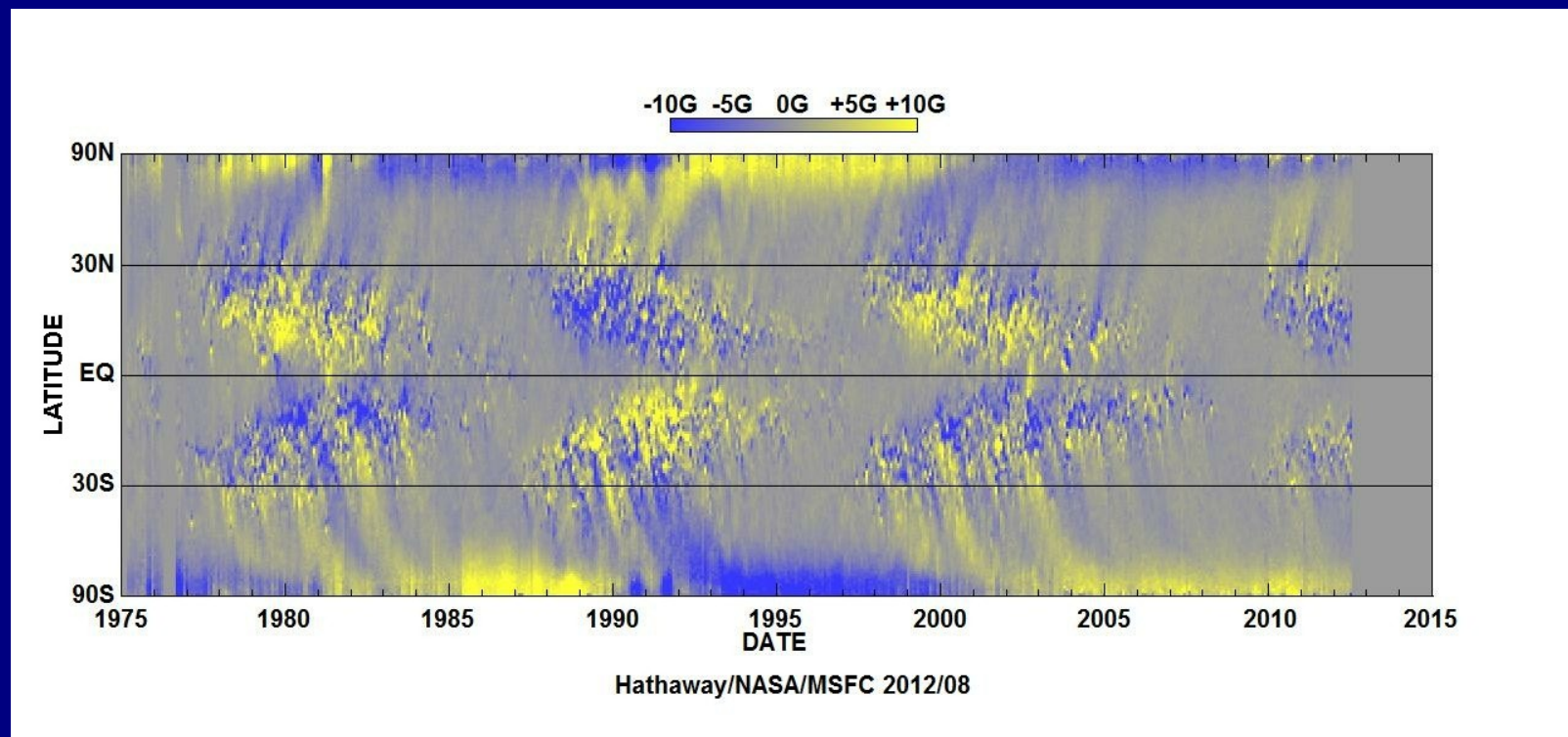
In addition to these magnetic polarity changes and the equatorward drift of the sunspot latitudes, there are important flows on the surface and within the Sun: *Differential Rotation* – faster at the equator, slower near the poles; and *Meridional Flow* – flow from the equator toward the poles along the surface.



Polar Field Reversals

In 1959 Babcock noted that the magnetic polarities of the Sun's weak polar fields also reverse from one cycle to the next, and that this reversal happens at about the time of sunspot cycle maximum.

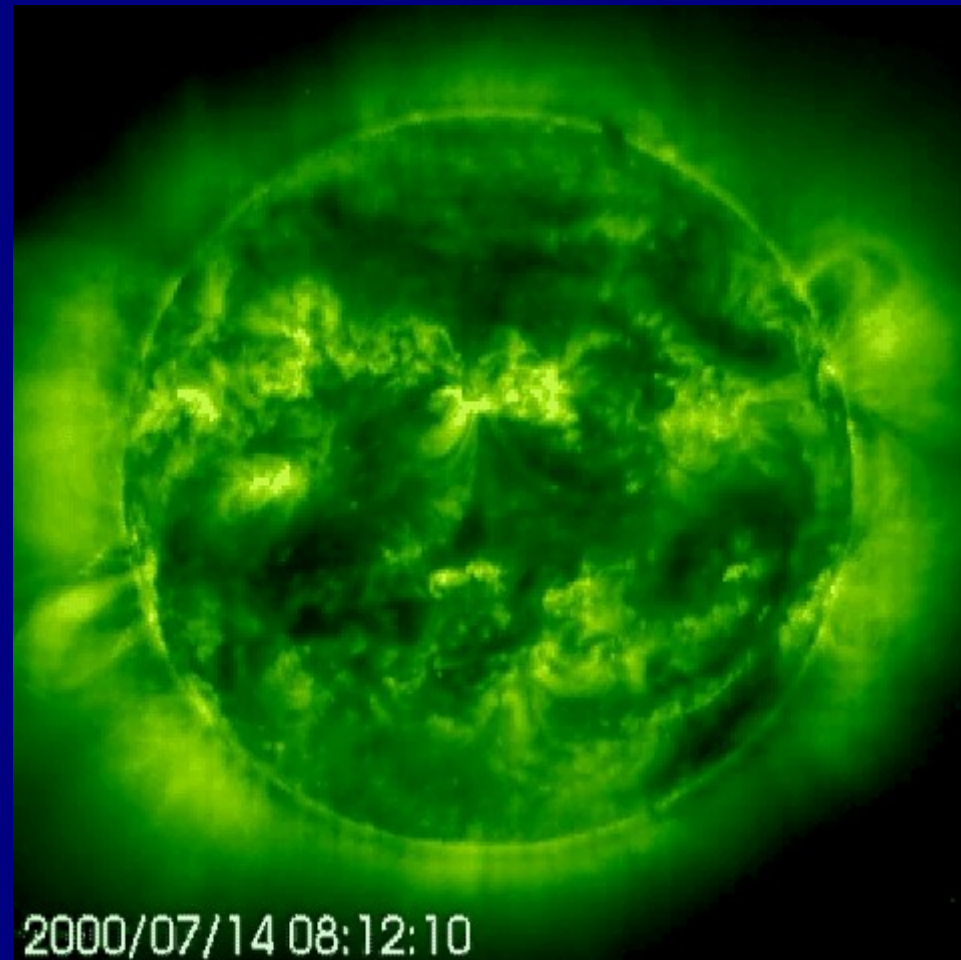
- About a month ago, solar scientist Todd Hoeksema announced that the Sun's magnetic field is three to four months away from field reversal.



Effects of the Sunspot Cycle

Explosive Events

- Solar flares – 10-1000X excess in X-rays and Extreme Ultraviolet (EUV)
- Coronal Mass Ejections (CMEs) – magnetic clouds blasted off the Sun
- Solar Energetic Particles – relativistic particles from flares and CMEs



CME Impact on Earth

Magnetized clouds of plasma blasted off of the Sun as CMEs can impact the Earth's environment – distorting the magnetic field surrounding the Earth and producing energetic particles that stream into the Earth's atmosphere to create aurorae.



Space Weather

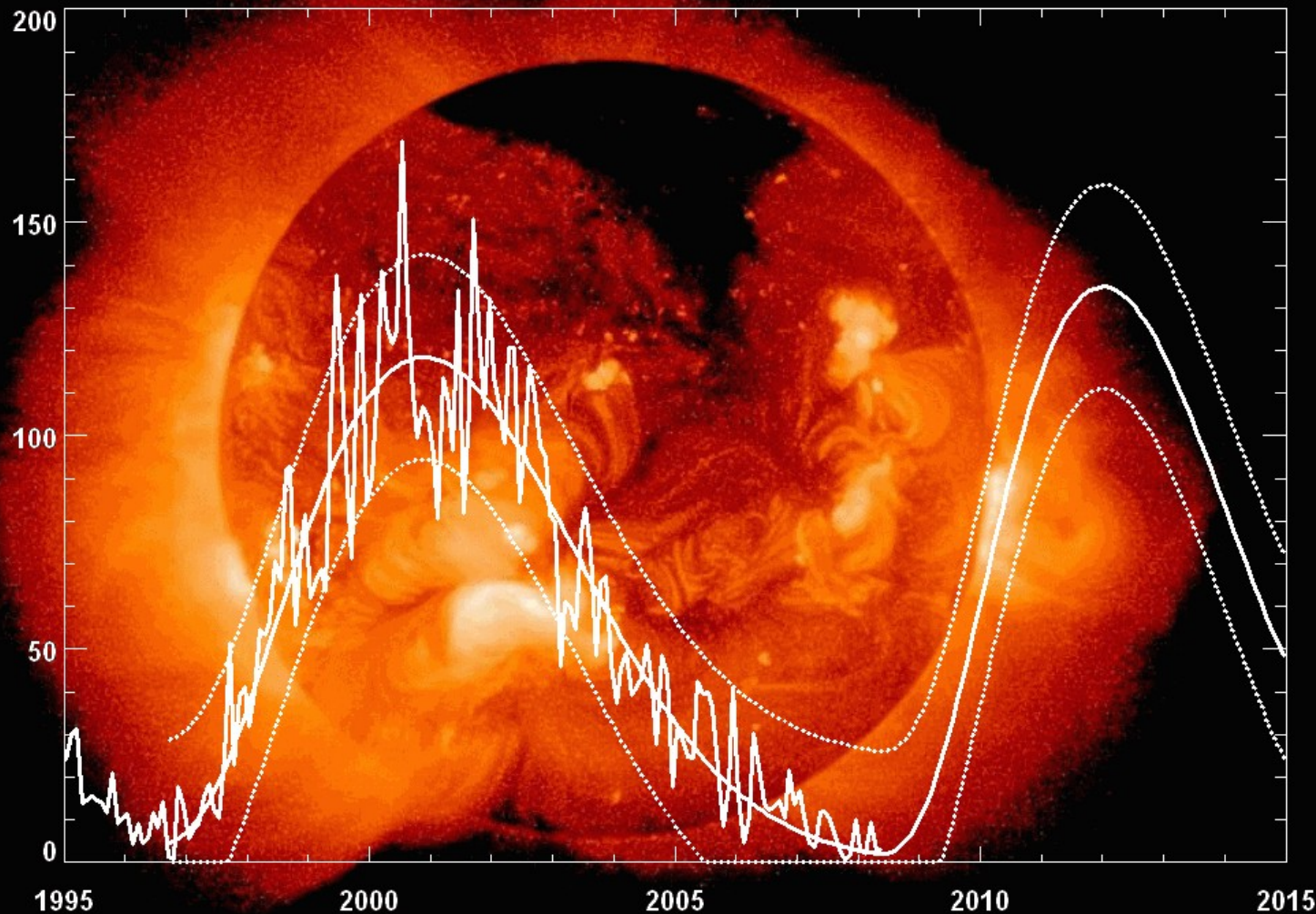
Space weather refers to conditions on the Sun and in the space environment that can influence the performance and reliability of space-borne and ground-based technological systems, and can endanger human life or health.



Solar Cycle Predictions

The Deep Solar Minimum Following Cycle 23

Cycle 23-24 Sunspot Number Prediction (June 2008)



NASA/MSFC/Hathaway

Spotless Days:

311 in 1913

250 in 1912

274 in 2009

266 in 2008

Length of cycle:

Cycle 23 – 12.6 yrs

Cycle 22 – 9.7 yrs

Cycle 21 – 10.3 yrs

Cycle 20 --11.7 yrs

Cycle 13 – 11.9 yrs

1890-1902

Cycle 14 --11.5 yrs

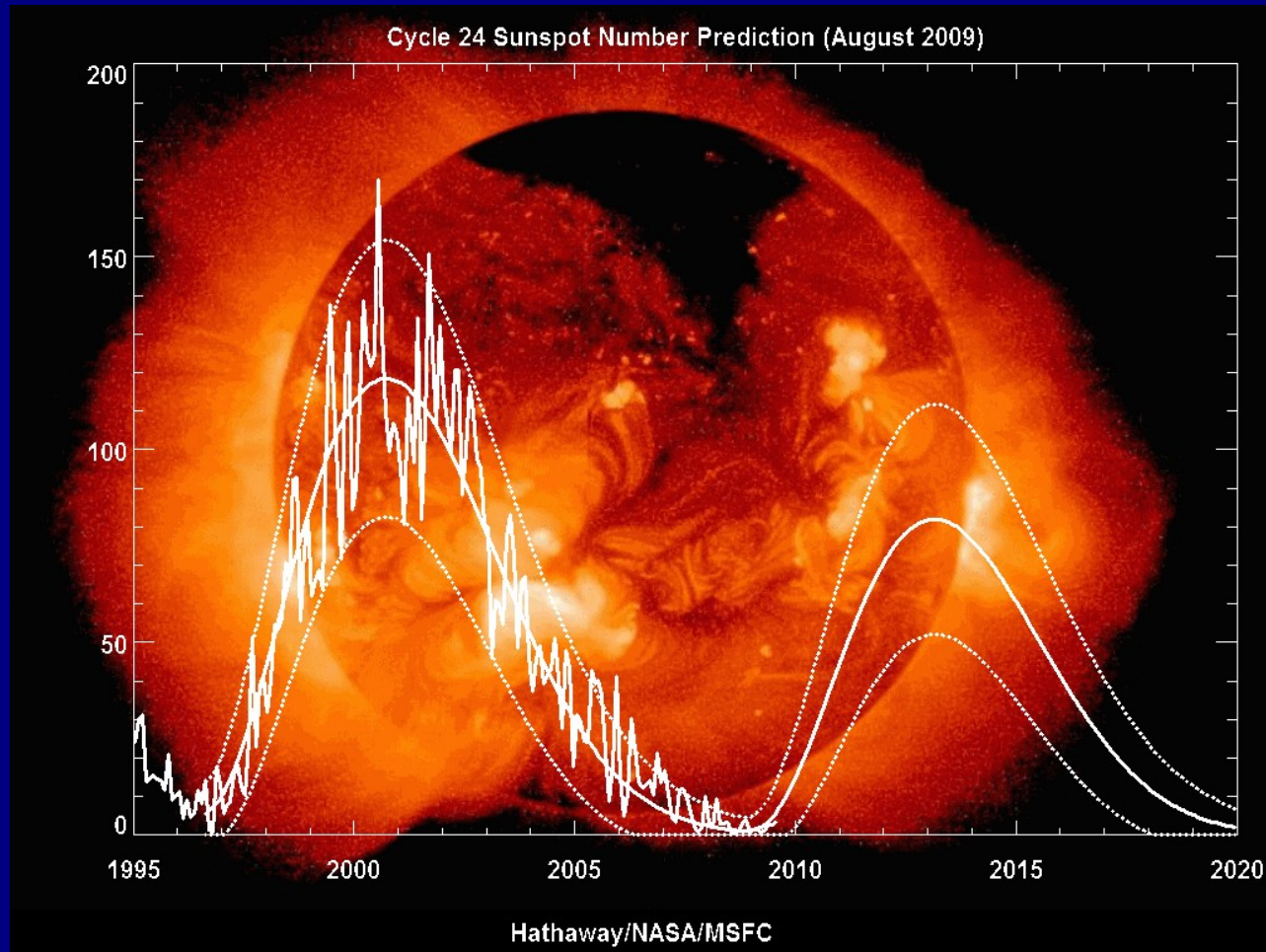
1902-1913

Cycle 15 – 10 yrs

1913-1923

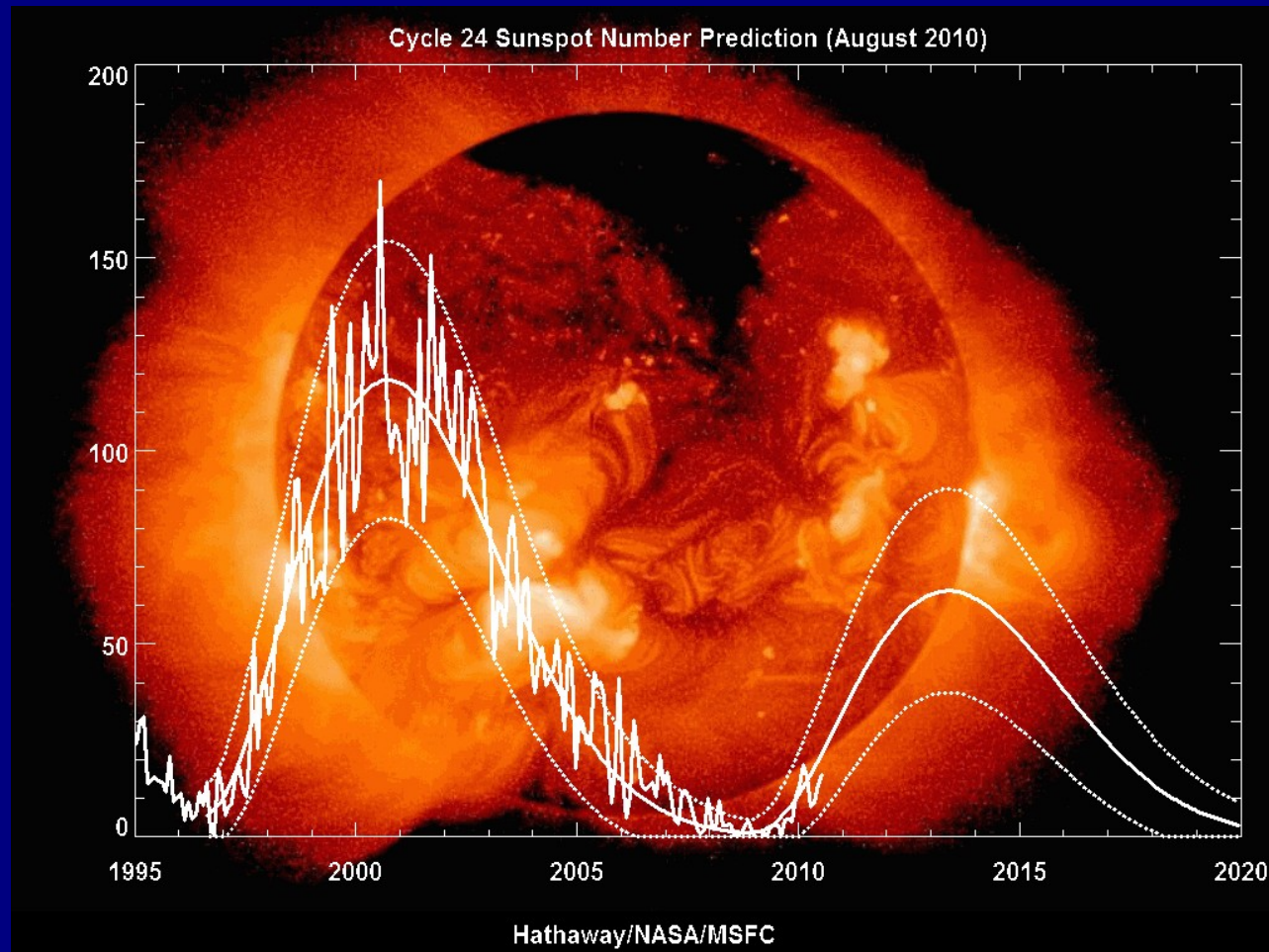
Four Years Ago

Small cycle predicted based on Polar Fields and Geomagnetism



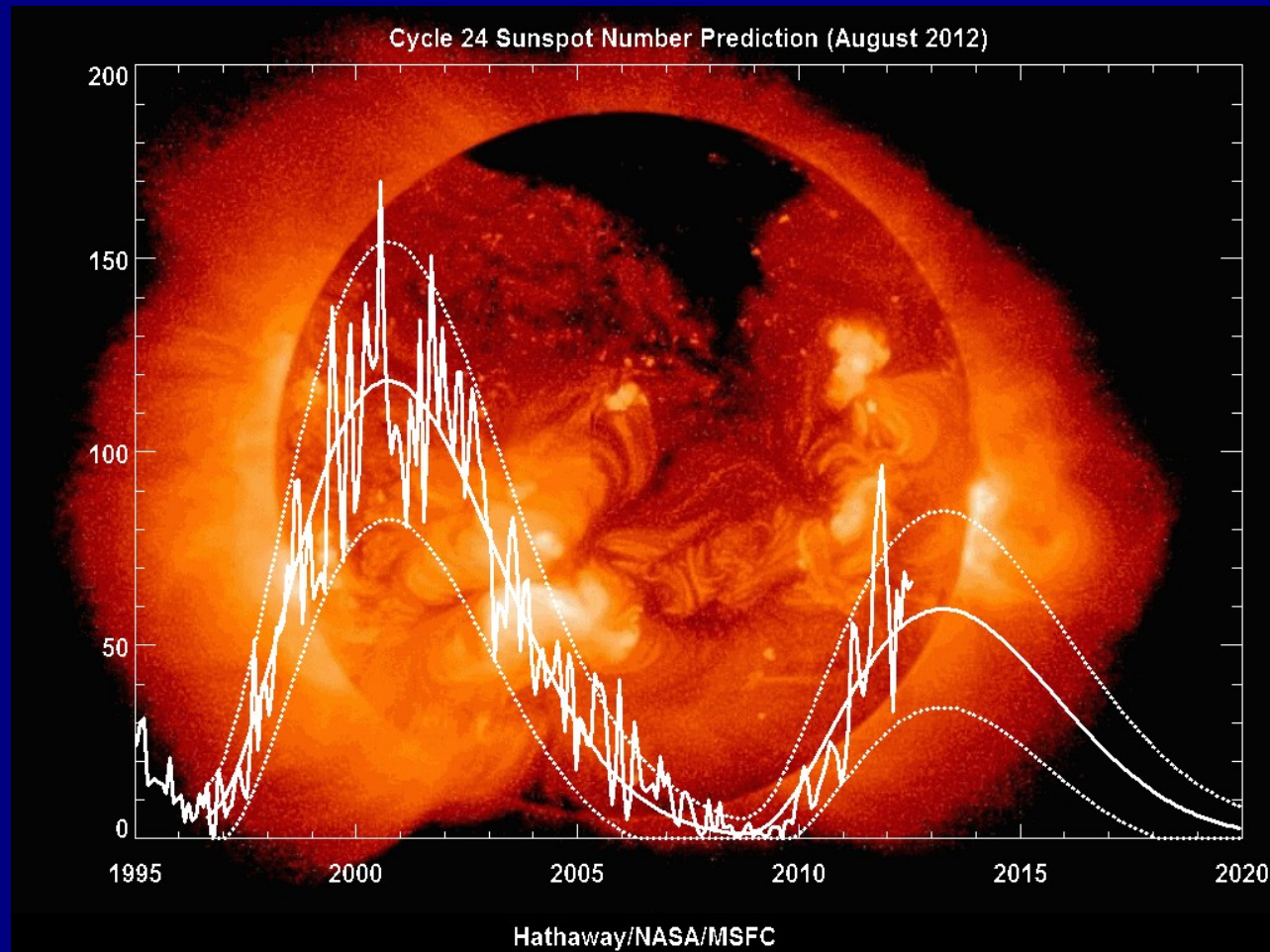
Three Years Ago

Including recent activity indicated an even smaller cycle.

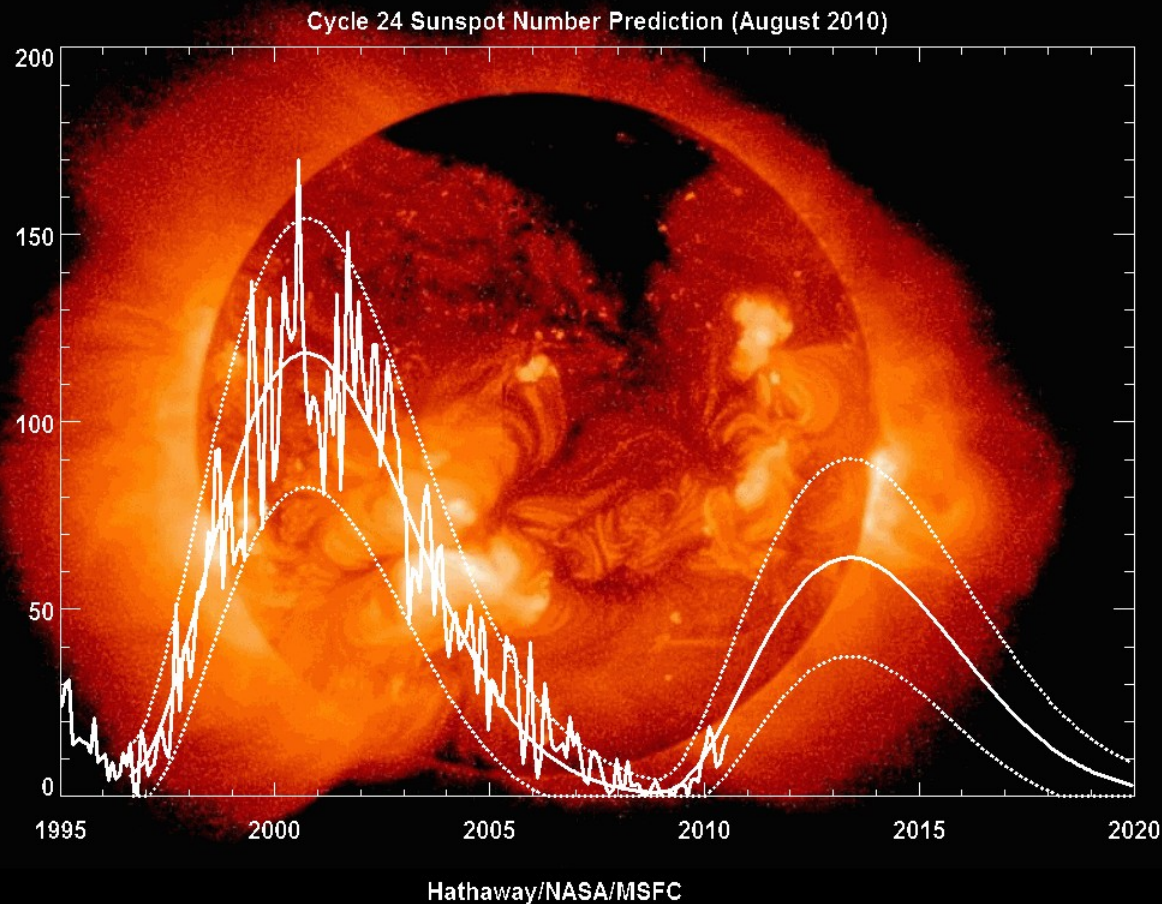


Last Year

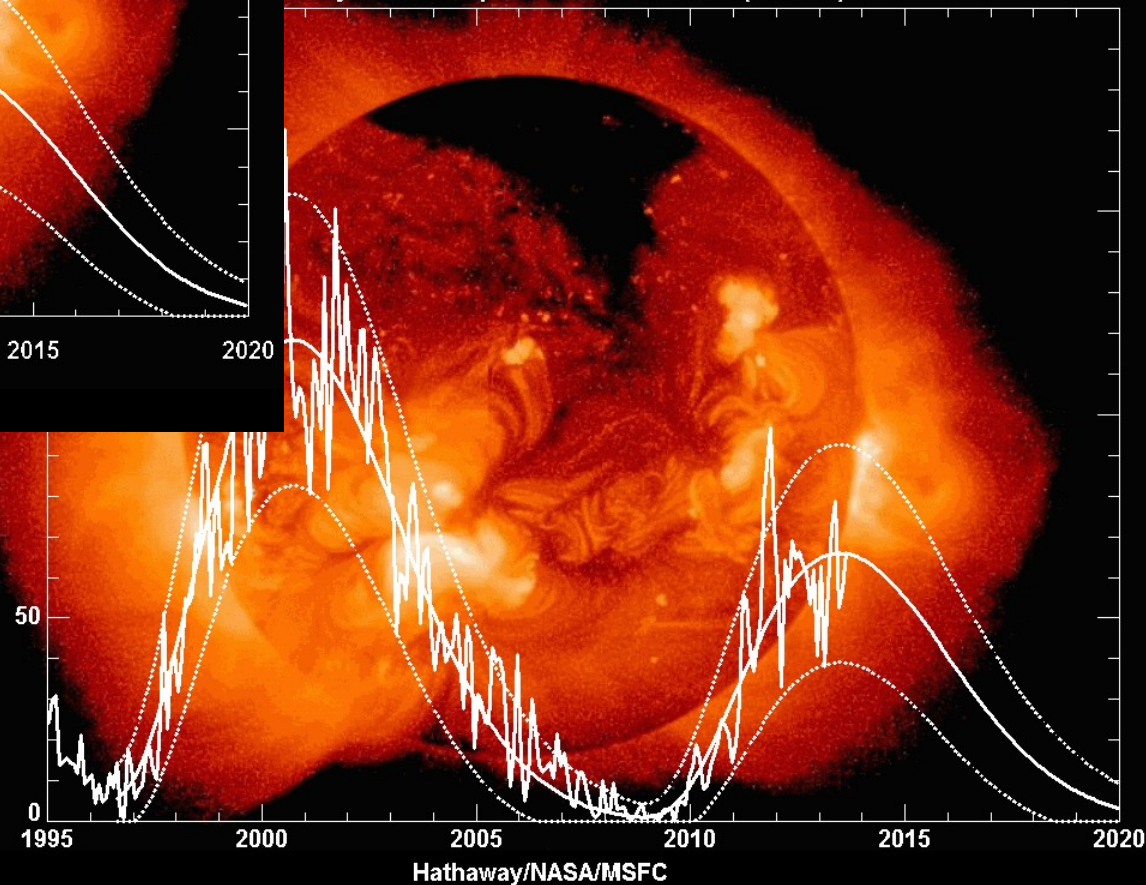
In spite of a flurry of activity late last year, the prediction dropped slightly – still indicating the smallest cycle in 100 years.



2010 Compared to This Year



Cycle 24 Sunspot Number Prediction (2013/09)



Conclusions

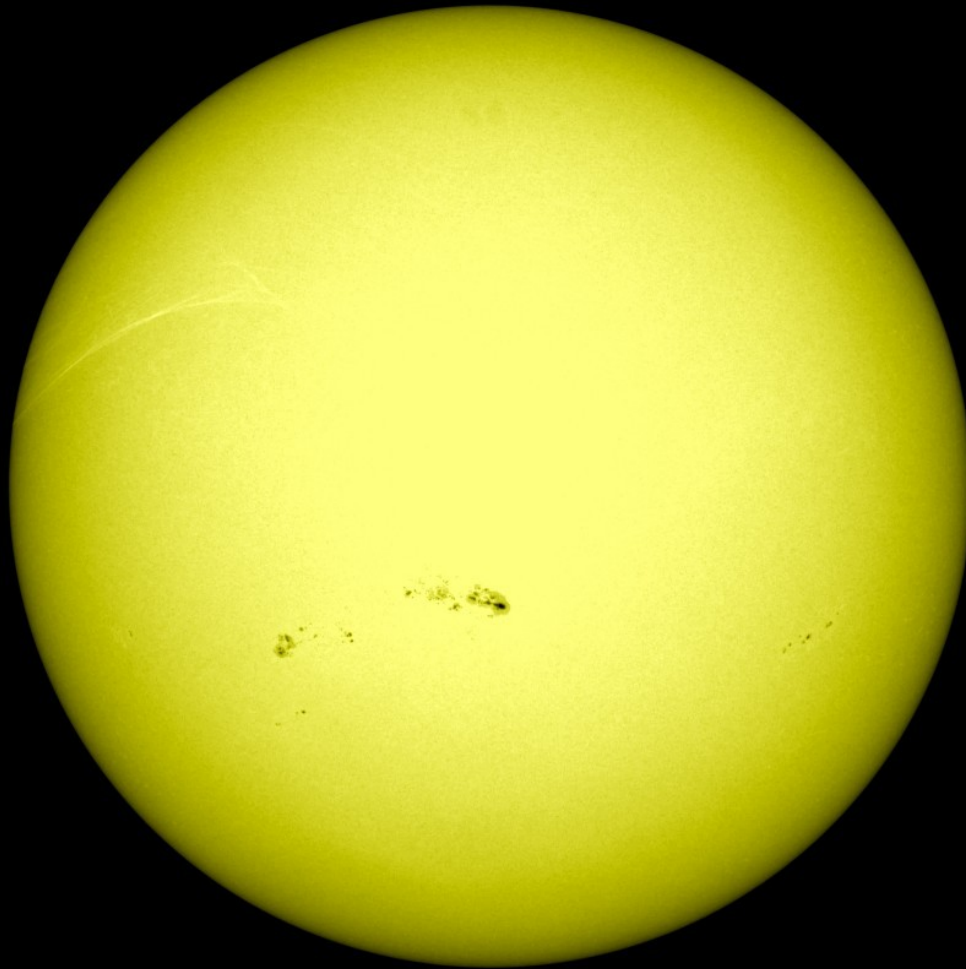
Through the use of observations, mathematics, mathematical tools (such as graphs), inference, testing, and prediction we have gathered evidence that there are sunspots, a solar cycle, and have begun to understand more about our star, the Sun.

We are making progress in understanding the cause of the solar cycle.

We expect solar cycle 24 to peak soon

Cycle 24 will be the smallest cycle in 100 years.

The Sun



Radius = $109 R_{\text{Earth}}$

Mass = $333,000 M_{\text{Earth}}$

Surface Temp = $9,930^{\circ}\text{F}$

Surface Density = Air/5000

Core Temp = 28 million $^{\circ}\text{F}$

Core Density = Gold $\times 8$

Composition: 70% H
28 % He
2% (C, N, O...)